BIO-ENERGY CHAINS FROM PERENNIAL CROPS IN SOUTH EUROPE

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ABSTRACT: This work refers to the EU project 'Bioenergy chains' (Contract No: ENK6-CT2001-00524). The overall objective of this project is to evaluate, in terms of technical, financial/economic and environmental feasibility, the whole bioenergy chain from biomass production to thermochemical conversion for a number of perennial energy crops carefully selected to ensure, by successive harvesting, a year-round availability of raw material. According to the data collected so far, the establishment, cultivation and harvesting of all four species were performed successfully, without needing new agricultural methods. The chemical composition of the perennial crops is closer to straw than woody biomass fuels therefore technologies for thermal conversion of straw should be considered for these crops. The basis for the economic and environmental assessments has been established. The results will be derived once the plantations have completed a full cycle.
Key words: energy crops, thermochemical production, economic aspects, LCA

1 INTRODUCTION

In the whole bioenergy chain, biomass production – processing – conversion, considerable time and funds have been spent so far on research solely for biomass production or energy conversion processes. Little attention has been paid yet to measuring and evaluating the performance of perennial and annual crops in an integrated bioenergy chain.

Use of a mixture of crops offers the potential for a year-round operation without the need to store large quantities of materials and feeding systems developed for energy crops and related materials would be capable of handling a wide range of materials with comparable handling characteristics.

Laboratory tests on the different stages of handling, pre-treating and processing these less commonly processed materials are an essential first step towards the development and the evaluation of integrated systems, particularly to compare performance on these materials with performance criteria derived from more orthodox biomass forms such as wood. Measures of product yield and product quality are particularly important.

This work refers to the EU project 'Bioenergy chains', Contract No: ENK6-CT2001-00524 [1] (see Table I).

2 APPROACH

The objective of this project is to define and evaluate complete bioenergy chains from biomass production to thermochemical conversion for production of valuable energy products. Four perennial energy crops, *Arundo donax* (Giant reed), *Cynara carduncululs* (cardoon), *Miscanthus x giganteus* (Miscanthus), *Panicum virgatum* (Switchgrass), are grown in southern Europe (Greece, Italy, France and Spain), which have been carefully selected to provide a year-round availability of raw material. These will be processed thermally by combustion, gasification and fast pyrolysis. The complete chains are being evaluated in technical, financial/economic and environmental terms in order to identify the most promising combinations of biomass resources and technologies (see Figure 1).

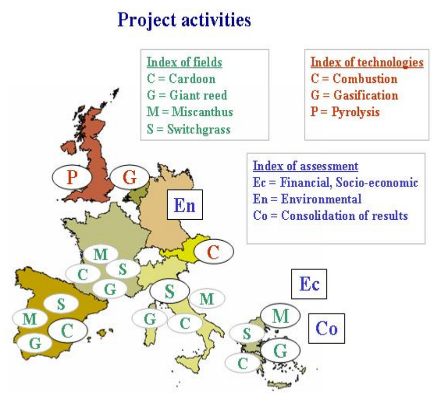

Figure 1: The project activities

Table I: The consortium and their involvement

The consortium		Involvement
CRES	Greece	Biomass production
UPM	Spain	"
UNIBO	Italy	"
INRA	France	"
ASTON	UK	Pyrolysis tests
VT-TUG	Austria	Combustion tests
BTG	Netherlands	Gasification tests
AUA	Greece	Financial/economic assessment
IFEU	Germany	Environmental assessment
IUS	Germany	"

Table II: Layout of the large scale fields

		Plant material		Equipment	
Crops	Location	Type	Density	Planting	Harvest
Arundo donax	Greece	rhizomes	0.9 plants m^{-2}	Semi-mechanically	Maize silage harvester
Cynara cardunculus	Spain	seeds	1.5 plants m^{-2}	Grain driller	Combine harvester + mower + rower + rotobaler
Miscanthus x giganteus	Greece	rhizomes	0.9 plants m^{-2}	Semi-mechanically	Maize silage harvester
Panicum virgatum	Italy	seeds	80-150 plants m^{-2}	Grain driller	Mower + baler

3 RESULTS

3.1 Biomass production

The four selected crops were established in large scale fields in Greece, Italy [5] and Spain (see Table II).

Apart from the large fields, all four perennial crops have been established in small-scale field trials in Greece, Italy, France and Spain, covering a total area of about 1 ha in each country.

In Greece, cardoon, giant reed and switchgrass were well established in 2002 and re-grew satisfactorily in 2003, while miscanthus field failed completely.

In Spain, giant reed grew well with irrigation. Miscanthus, though treated the same way as giant reed did not perform that well; the plant density was considerably low. The performance of switchgrass was also rather poor, probably because the strong competition with weeds.

In Italy, cardoon, giant reed and switchgrass were well established in 2002 and their re-growth in 2003 was very satisfactory. Miscanthus failed completely because rhizomes were planted too late in the season.

Cardoon, giant reed, switchgrass and miscanthus were established in March 2003 in South France. However, due to adverse climatic conditions in summer 2003, the fields were destroyed and replanted the following year.

3.2 Fuel characterisation

Samples of all harvested materials were sent to ASTON, BTG and VT-TUG for their fuel characteristics tests.

ASTON has conducted ash content measurements. The values reported are generally consistent with ranges reported within literature. In the case of giant reed, it was noticed that the leaves contain about twice the amount of ash as the stems, however, the dry matter proportion of leaves is low, which means that overall ash content is not dominated by leaf material. Very high ash contents in pelletised materials have been measured by VT-TUG (17% for cardoon and 23% for switchgrass). This high ash content is mainly due to high amounts of Si and Ca in the ash and is higher in the pelletised switchgrass material compared with manually cut samples. This high ash content usually indicates soil contamination during the harvest and pelletisation. It is therefore important to distinguish whether ash levels measured during the project are due to the plant physiology, the mineral composition of the soil and the fertilisers applied or whether are they are present as contamination.

The tests on the chemical composition of the crops indicated particularly high levels of Na, P, Ca and Cl in cardoon, high levels of P and Cl in giant reed and the potential for high levels of P and Cl in all four perennials.

As for the calorific value of the crops, it ranges from 17.5 MJ/kg to 18.8 MJ/kg and lie within the range of reported values in the literature.

BTG had performed additional ash melting tests. Some high-ash cardoon samples have been tested which –contrary to the previous samples- showed a normal ash melting behaviour. Additionally, ash samples obtained after combustion of the biomass have been analyzed and their behaviour was very similar to the original ash.

Detailed data are reported in [2] & [3].

3.3 Combustion tests

A set of laboratory scale test runs and tests runs at a pilot scale combustion unit has been performed by VT-TUG; see also [3]. The first observation that could be drawn from the pictures of the ash from chopped material is the dark colour of this ash which indicates a high content of unburned carbon. A second observation is the high volume of this ash which almost resembles the volume of the fuel sample itself. The density of this ash is very low (light and voluminous) and thus ash can easily entrain from the fuel bed to the flue gas.

In contrast to the chopped material ashes from the pelletised materials are grey or light brown, indicating a complete burnout of these fuel samples. Although a complete burnout was reached, still a very voluminous ash was produced, and the structure of the pellets remained in the ashes. Furthermore, these ashes also showed significant signs of sintering and ash melting.

During the test runs with chopped samples the temperatures in the bed were significantly lower than during the test runs with the pelletised materials. The reason for this is the low density of the chopped fuel. The lower combustion temperature of the chopped samples is also the reason for the poor burnout of these samples.

Low concentrations of Cl and S were found in the flue gas, indicating that the main part of the Cl and S, which is released from the fuel during the combustion, forms solid fly ash particles in the flue gas already inside the reactor above the fuel bed.

During the test runs with the pelletised fuels sintering and melting of the ash was observed and consequently, these samples were sent to partner BTG for more detailed melting analyses. The results from these melting tests suggest that at a slightly lower combustion temperature in the bed could avoid ash melting.

Particle measurements were performed which showed high amounts of unburned carbon (soot) and tar in the flue gas after the secondary combustion part.

However, after each of the test runs with Cardoon it was observed that the inside of the reactor was completely covered with a layer of white particles. Previous experience from biomass combustion and the high concentration of Cl in the Cardoon sample strongly suggest that these particles consist predominantly of salts (eg. KCl and NaCl). This is also a strong indication for the formation of submicron fly-ash particles (aerosols) from this fuel.

3.4 Pyrolysis tests

A single test was performed on cardoon to re-commission the 100gph pyrolysis rig. The test was performed at a temperature of 543°C. The ash content of the sample used was 5.28% and this led to a high yield of char. The char density was very low leading to overflow of the char collection vessel and significant contamination of the bio-oil collected.

The oil produced was highly phase separated with a high mass fraction being a watery phase collected in oil pot 2 with a very unpleasant odour indicative of high levels of ketones and aldehydes. This is typical of oils produced at higher temperatures and/or from high ash content feedstock.

Because of the problem of char pot overflow it was decided to continue testing on a lower ash content feedstock and to procure a larger char pot.

Five successful tests have been performed on Arundo donax using the 100g/h fluidised bed rig. The feedstock was ground to a maximum particle size of 0.5 mm and then sieved to produce a feedstock with a particle size in the range 355 to 500 µm. This prepared material had an ash content of around 4.2 wt% on a dry feedstock basis.

The first four tests determined the baseline pyrolysis product yields at a range of pyrolysis temperatures. The 5^{th} test was performed on a cold-water washed sample with an ash content of 2.75%. This test investigated the potential for improving organic liquid yield by reducing the ash content of the biomass.

The maximum yield of organic liquids (i.e. all liquid products minus water) for Untreated Arundo is around 45% on a dry basis (which equates to nearly 48% on a dry ash free basis).

Washing the feedstock to achieve an ash reduction from c.4.2% to 2.75% has led to an increase in the yield of organic liquids (c.12% d.b.) and a reduction in the yields of char, gas and water of pyrolysis (products of condensation reactions). The improvement brings the organic liquid yield for this feedstock into alignment with the best of other high ash biomass; however it is still up to 15% lower than the best wood feedstock. Clearly further improvement might be made with greater ash reduction from improved washing.

The pyrolysis liquids from the baseline tests had high water content e.g. 34.7 wt % for an oil produced from feedstock with a 9.8 wt% moisture content (wet basis) and this is indicative of phase separation in oils collected in a commercial process.

3.5 Gasification tests

BTG received samples of the selected biomasses for testing in the feeding section of the bubbling fluidised bed gasifier.

Round bales of switchgrass have been gasified for nearly 4 hours without any operational problem. The operation temperature was chosen to be rather low to ensure that no ash melting or sintering will occur. No chlorine was detected in the producer gas.

Cardoon was also in the form of round bales, which after size reduction became a very "fluffy" material that caused problems in the feeding machine.

The gasification test was carried out under very similar conditions as for switchgrass. The temperature of the gasifier was limited to about 700 °C to reduce the risk of ash agglomeration. The experiment has lasted for about one hour. During the experiment a continuous increase of pressure drop across the gasifier was observed. After cooling down of the gasifier the internals of the gasifier could be inspected. In the internal cyclone and in the bed-material large particles of agglomerated material were found. As a result the cyclone was completely filled with sand causing a high pressure drop.

The ash of this cardoon sample was tested on its melting behaviour. The initial deformation temperature suggests that ash agglomeration will not occur in the gasifier. Similar to the cardoon pellets the ash content was much higher than of the first cardoon samples, and probably the samples contained some soil. In the gasifier a separation of the real ash and soil may occur, and therefore the behaviour might be completely different than expected on basis of the ash melting test.

4. FINANCIAL/ECONOMIC ASSESSMENT

BEE (Biomass Economic Evaluation) model has been developed by AUA, in order to perform full economic analysis of energy crops production [4]. The model may analyse annual and/or perennial energy crops. It can also be used to analyse a single plantation or combination of crops. It is a standard MS Win XP based application with internet support (http://www.bee.aua.gr) that provides detailed monthly monitoring of operation needs (labour, raw materials, and machinery including fuel consumption). The model carries out full economic analysis by agricultural operation/activity (Activity Based Costing) and by factor of production. The estimated cost is reported by ton, by hectare, etc. BEE performs full financial analysis in standard accounting form and identifies all relevant cash flow of each crop in order to evaluate projects incorporating more than one crop. The model has easy to understand input forms and reports.

Using BEE and the collected data of the four energy crops, a primary cost analysis of energy crops production was performed. The primary result is the production cost of the four perennial crops per ton and per ha. The estimated cost is separated into two main categories: (a) cost by operation and (b) cost by factor of production.

From this analysis, miscanthus seems to have the highest production cost per ton and giant reed follows. Both crops have significant demands for irrigation, which means that they have additional cost of irrigation and increased land rent of irrigated land. Both of them are also planted using rhizomes, which is the most expensive method of establishment, because it has great human labour demands and high cost of rhizomes.

Switchgrass and cardoon have significant lower cost per ton than the other two crops because they do not have irrigation needs and are cultivated on non-irrigated land that is characterised by lower rent than irrigated land. They are also established with sowing, which has much lower needs for human labour than establishment with rhizome cuttings and also, the cost of seeds per land unit is much lower than the corresponding cost of rhizomes.

More representative results will arise from further cost analysis using more representative data from project's large experimental fields.

5 ENVIRONMENTAL IMPACT ASSESSMENT

Compared to fossil fuels, all investigated energy crops save noteworthy amounts of finite energy and greenhouse gases. Concerning other environmental implications the results behave vice versa or equal to zero.

Comparing the four crop species, giant reed and miscanthus seem to have slightly better environmental results than switchgrass and cardoon. But in a year-round system, all energy crops have to be used. Cardoon has the advantage of being indigenous to the Mediterranean flora and to provide food for insects and granivorous birds. However, the specific management regime is likely to have a larger influence on the environment then the plant specific characteristics. All investigated energy crops provide environmental benefits compared to annual crops, with respect to soil erosion, soil compaction, soil chemistry, eutrophication and habitat quality. However, impacts are mixed if perennial energy crops substitute extensively used grassland, pasture or fallow land and most probably negative, if the energy crops replace natural land.

The environmental impact further depends on how the crops will be integrated within the landscape (enhancement / reduction of landscape diversity) and the spatial relation to similar habitats.

From the environmental point of view, direct combustion of the energy crops is favourable to gasification and pyrolysis in many cases.

For indicating the best options or systems, all technological, environmental, economic and social aspects have to be considered.

6 CONCLUSIONS

The establishment, cultivation and harvesting of all four species were performed successfully using conventional agricultural methods. Yields of each crop varied considerably according to site and climate and increased dramatically from the establishment year to the second one in all sites. The respective dry matter yields of 7-28 t/ha were reported for Arundo donax, 3-16 t/ha for Cynara cardunculus and 3-28 t/ha for Panicum virgatum. In Greece and Italy A. donax and P. virgatum have performed the best, while in Spain A. donax and C. cardunculus were the best adapted crops. There is a general trend for higher yields in sites where water is not a limiting factor.

High ash contents for all crops (2.9% to 5.3%) were measured compared to woody feedstocks and also significant variability in both ash content and ash composition. Higher Heating Values (HHV) are ~17.5 to 18.5 MJ/kg. Correlation of ash content and chemical composition with the agricultural practices used has to be done, in order to maximize the yield of dry biomass whilst minimizing the use of fertilizers known to contain detrimental minerals. The concentration levels of relevant elements (especially K, Na and Cl) are comparable with straw. Pelletisation and mechanical harvest can significantly increase the ash content of the fuel due to inclusions of soil contamination. Thus care has to be taken during harvest not to unnecessary contaminate the fuel.

Miscanthus and giant reed seem to have the highest cost of production per hectare and per ton because of their significant demands for irrigation (cost of irrigation, increased land rent of irrigated land) and their establishment using rhizomes (the most expensive way). Switchgrass and cardoon are less costly as they have little or no demands for irrigation and they are established with seeds (lower labor and cost of seeds).

Compared to fossil fuels, these crops save finite energy and greenhouse gases. Giant reed and miscanthus seem to have slightly better results than switchgrass and cardoon. Cardoon has the advantage of being indigenous to the Mediterranean flora and provides food for insects and birds. Compared to annual crops, they provide environmental benefits with respect to soil erosion, compaction, chemistry, eutrophication and habitat quality. Direct combustion is favorable to gasification and pyrolysis in many cases.

For indicating the best options or systems, all technological, environmental, economic and social aspects have to be considered.

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